Moroccan Crustal Response to Continental Drift

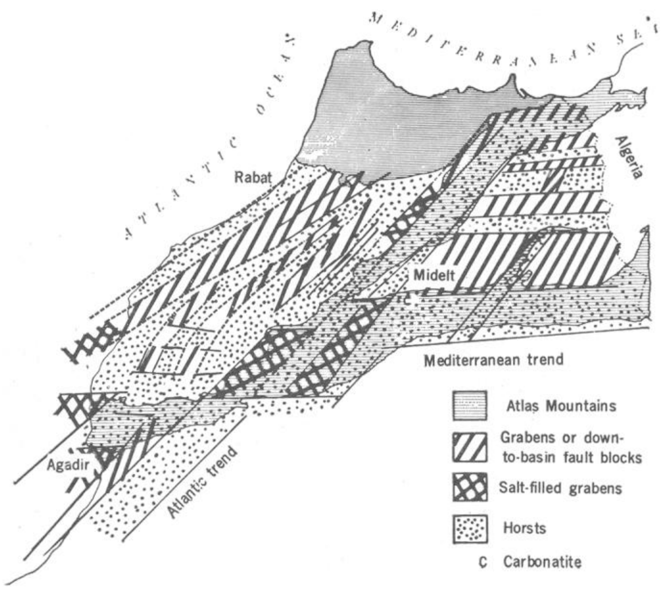
Abstract. *The formation and development of a zone of spreading beneath the continental crust resulted in the breakup of Pangea and formation of the Atlantic Ocean. The crust of Morocco bears an extremely complete record of the crustal response to this episode of mantle dynamics. Structural and related depositional patterns indicate that the African margin had stabilized by the Middle Jurassic as a marine carbonate environment; that it was dominated by tensile stresses in the early Mesozoic, resulting in two fault systems paralleling the Atlantic and Mediterranean margins and a basin and range structural-depositional style; and that it was affected by late Paleozoic metamorphism and intrusion. Mesozoic events record the latter portion of African involvement in the spreading episode; late Paleozoic thermal orogenesis might reflect the earlier events in the initiation of the spreading center and its development beneath significant continental crust. In that case, more than 100 million years were required for mantle dynamics to break up Pangea.*

Plate tectonics has proved a powerful tool for interpreting the significance of the geophysical, geochemical, and petrologic consequences of crustal dynamics. The primary manifestation of the interaction between the relatively passive crust and the dynamic mantle is the formation of crust along spreading centers and consumption of crust along subduction zones. These, as well as ancillary features such as ridge systems, magnetic stripes, and transform faults, are clearly observed in the thin, basaltic oceanic crust. When spreading occurs beneath continental crust, these features are not clearly apparent. This is understandable: the "granitic" composition and greater thickness of continental crust ensures a characteristic "continental" response to mantle dynamics. One of the major goals of continental geology should be the recognition of continental equivalents of the geodynamics now observed on the ocean floors.

The Atlantic margins of the Americas, Europe, and Africa contain information concerning the fragmentation of Pangea during a major episode of crustal spreading beneath continental crust. One of the regions best suited for analyzing the imprint of Pangea's fragmentation is northwest Africa. Unlike North America, much of the African record of continental rifting is still intact, being neither obscured by later tectonic events nor buried beneath a blanket of more recent sediments. An international study team under the auspices of the University of South Carolina, the Service Géologique du Maroc, the Moroccan Bureau de Recherches et de Participations Minières, and the National Science Foundation has been assembled to gather paleontologic, stratigraphic, geophysical, and igneous and metamorphic petrologic data which will be used to synthesize a crustal response model for the Kingdom of Morocco. We present here some of the current results.

Present-day Morocco consists of two Precambrian-Paleozoic terranes separated by the Mesozoic trend of the High Atlas and Middle Atlas mountains (*1*). The southern margin of this trend is bounded by the Precambrian and lower Paleozoic terranes of the Anti-Atlas Mountains. The northwest boundary is formed primarily by massifs consisting of metamorphosed and intruded Paleozoic strata. In addition, isolated massifs occur within the dominantly Mesozoic trend of the High Atlas. Mesozoic strata are present locally in the area of the High Plateau between the High and Middle Atlas. The Rif, a Tertiary nappe terrane in northwesternmost Morocco, is not relevant to this study.

The older Paleozoic and the Precambrian were broken by a series of block faults in which Mesozoic sediments were deposited. The faults fall into two vectoral families (Fig. 1); the first trends about N45°E, essentially parallel to the present Atlantic shelf



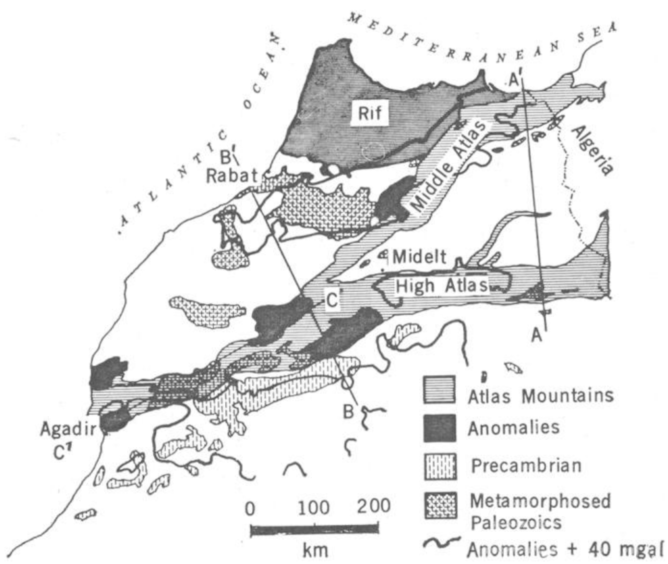


Fig. 1 (left). Pattern of late Paleozoic and early Mesozoic faulting. Fig. 2 (right). Gravity anomalies [after Van der Bousch (*7*)] and their relationship to Precambrian and Paleozoic massifs. The areas with Bouguer anomalies greater than 40 mgal are enclosed by the +40-mgal isopleth. The areas designated as "anomalies" represent strong negative gravity residuals which cannot be accounted for by a simple layered basement model. These features were recently discovered by Van der Bousch and are more completely discussed by him (*7*).

edge; the second trends about N80°E, or roughly parallel to the Mediterranean coastline of Morocco. These fault systems are present over most of Morocco, with the N80°E trend (the "Mediterranean trend") dominant nearer the Mediterranean and the N45°E trend (the "Atlantic trend") dominant nearer the Atlantic margin. This tensional pattern can be recognized in different ways in different areas. Northwest of the Atlas trend (the Moroccan Meseta), the faulted terrane is exposed and has been mapped (*2*). In this region, as well as the High Plateau, tectonic patterns are determined from subsurface well data (cross section *B-B′* in Figs. 2 and 3 is based on 19 wells; section *A-A′* is drawn on the basis of nine wells and limited seismic data).

The trend and style of Mesozoic deformation in the Atlas Mountains are determined on the basis of data from diverse sources. In the Atlas east of Agadir the trends are clearly displayed and have been mapped (section *C-C′* in Figs. 2 and 3). Fault patterns in the central High Atlas south of Midelt have been inferred from the orientation of Mesozoic dikes and the prismatic-shaped, positive gravity anomalies which define the boundaries of horsts (Fig. 2) (*3*). In the High Atlas east of Midelt, grabens of the Mediterranean trend are filled with Mesozoic sediments derived from the contiguous horsts (*4*). Atlantic trend horsts and graben in the Middle Atlas have been inferred from the shape and orientation of positive gravity anomalies, aerial photograph lineations, and published data (*2*). The Tarfaya region in extreme southwest Morocco is dominated by similar Atlantic fault trends (*5*).

Seismic investigations of the Atlantic shelf indicate that the tensional fault style observed onshore continues into the offshore (*3*). As observed onshore, the seaward extension of the Atlas trend has the same fault style as neighboring regions of the shelf (*3*).

Field studies in the Argana and Ourika valleys (*6*) in southwest Morocco and subsurface data from the High Plateau indicate that faults in these areas were concurrent with and controlled the patterns of lower Mesozoic sedimentary accumulation (see Fig. 3). Detrital sediments rapidly thicken and become coarser-grained toward the faults bordering these Mesozoic sedimentary basins. Adjacent to the faults, fanglomerates several thousand meters thick were deposited. These fans rapidly give way to deltaic facies which, in turn, grade laterally into gypsums and dolomites. Salt and marine limestone facies interfinger with the carbonates and sulfates in a more seaward direction.

The origin of the salts can be explained by down-dropping of the continental margin with concomitant periodic incursion of seawater followed by episodes of evaporation. It is equally likely, however, that uplift of cratonic Africa induced drainage of marine surface waters and sediment pore waters. These salt waters were carried by surface runoff to the margins of the continents during the late Paleozoic and early Mesozoic; this provided the requisite salt for subsequent evaporites. Whatever the source of the water, it is clear that the "checkerboard" pattern of Mesozoic faulting provided one of the controlling mechanisms for evaporite deposition. Drainage through a complex network of grabens would have been slow, enhancing the probability of evaporation and salt precipitation.

In the past, the Atlas Mountains have been considered a structural and stratigraphic province, as well as a physiographic province. The block-faulted structural style observed elsewhere in Morocco, however, continues uninterruptedly in the Atlas. Gravity anomalies (Fig. 2) indicate that the relatively small and isolated metamorphosed Paleozoic massifs therein are the surface expression of much larger blocks. These blocks are thinly veneered by Jurassic carbonates; subsurface and seismic data show that the contiguous downthrown blocks were Jurassic and Triassic depositional basins (Figs. 1–3). Several of those grabens contain thick salt sequences and induce strong, compensated gravity anomalies (*7, 8*). Salt mines, and structures which appear to be salt diapirs or salt walls (*9*), also are associated with the salt-filled grabens. Reefs commonly grew on the crests of folds induced by diapiric emplacements, which suggests that the salt was mobile during the Jurassic.

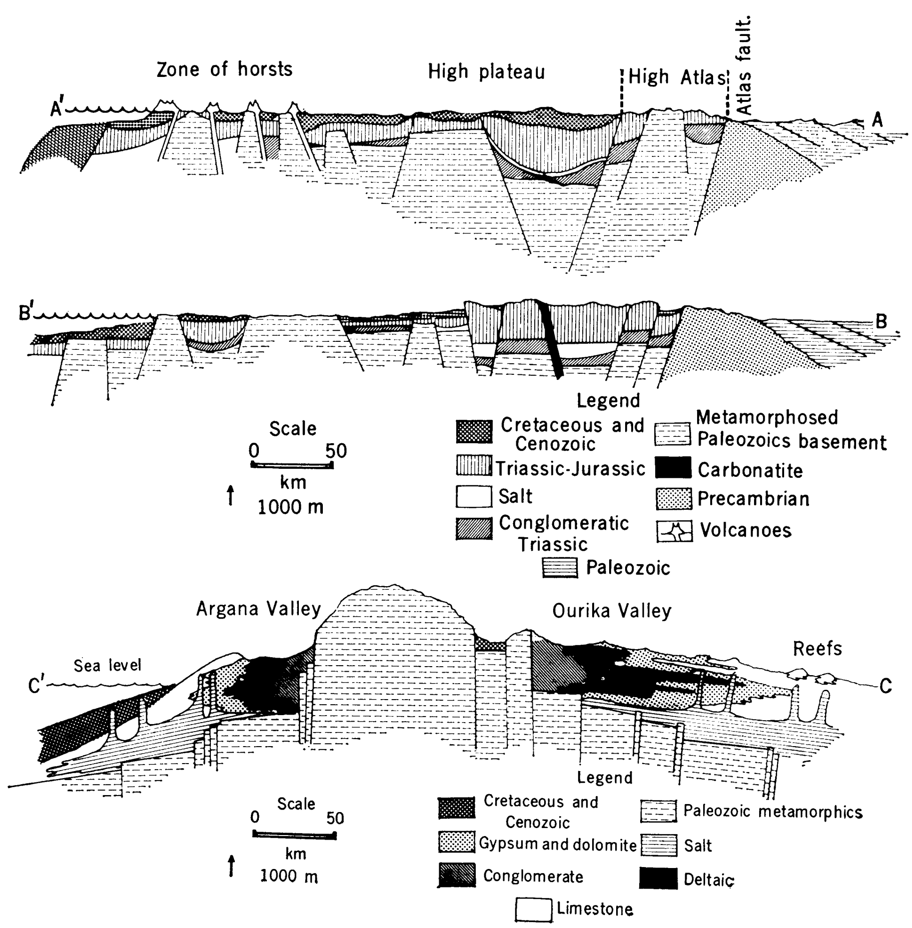


Fig. 3. Cross sections along lines designated on Fig. 2.

The present relief of the Atlas Mountains is the result of selective reactivation of Mesozoic faults by late Tertiary and Quaternary tectonics. These late movements probably remobilized the Mesozoic salt, producing higher elevations over the salt-filled grabens.

The late Cenozoic stresses have their greatest release where Mesozoic carbonates and clastics bordered Paleozoic or Precambrian metamorphic and igneous complexes. The present High Atlas Mountains were activated along faults parallel to the Mediterranean trend, where the Precambrian is contiguous to the Mesozoic carbonates (Fig. 3). The same geological situation pertains to the Middle Atlas Mountains, which are contiguous to the metamorphosed Paleozoic rocks of the Moroccan Meseta.

Tensile stresses were dominant in Morocco during the early Mesozoic. The orientation of the fault planes suggests that the tension was connected with the opening of the Atlantic and the Mediterranean. These faults became dormant or subdued during the Jurassic, when the area was subjected to marine inundation that blanketed the earlier facies and structures with limestones. By Late Jurassic, sufficient new crust had been added to isolate Morocco from the dynamics of sea floor spreading. The tensional tectonic style of the earlier Mesozoic suggests that, even then, the area was marginal to the zone of spreading.

Much of the pre-Mesozoic "basement" consists of thermally metamorphosed and intruded Paleozoic strata. In fact, strata as young as Westphalian (*2, 4*) have been affected, as well as older sediments. These metamorphosed terranes have been termed "Hercynian" (*2, 3*) (a mid-Carboniferous orogeny) whereas they have a much more complex and long-ranging history.

It seems likely that thermal events, with attendant orogeny, immediately preceded Mesozoic tension. If we assume that this tension represents the closing phase of African involvement in continental drift, then the preceding thermal events may represent the effects of early intrusions into the continental crust as the zone of spreading was initiated. A similar sequence of metamorphism followed by tensional faulting has been described for a portion of Baja California, an area presently undergoing drift (*10*).

If it is assumed that both the earlier thermal events and the later tensional events are the sequential results developed in response to a zone of spreading, then more than 100 million years were required for mantle dynamics to break up this portion of Pangea.

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Age of the Floor of the Eastern Indian Ocean

Abstract. *Deep sea drilling in the eastern Indian Ocean shows that the oceanic crust off Western Australia is approximately 140 million years old and becomes younger to the west; this dates the initial opening of the Indian Ocean.*

In the reconstruction of continents to restore the ancient supercontinent of Gondwanaland the positions of the continents around the Indian Ocean have been especially enigmatic. Several papers have suggested fits of the continents based mainly on a fit of the margins of bordering continents (*1*), on extrapolations of marine geophysical structure to the edges of the ocean (*2, 3*), and on geological similarities of bordering continents (*4*). These studies indicate that the Indian Ocean has opened by the mechanism of sea floor spreading and continental drift, but with complications caused by the existence of more than one major spreading pattern. The marine geophysical record since the beginning of the Tertiary or the Late Cretaceous (the last 75 million years) has clarified the more recent history of the ocean. Before that time the record is obscure. Recognizable linear magnetic anomalies are useful for dating sea floor younger than about 75 million years, but linear magnetic features can rarely be recognized in the area that is presumably older. Accordingly, the age of initial rifting of the bordering continents and the direction of their initial movement have been matters of controversy.

On leg 27 of the Deep Sea Drilling Project (*5*) a series of holes have been drilled through the sediment cover and to the ocean basement in the area off Western Australia—an area which was previously thought to be the oldest in the Indian Ocean, if not in all the oceans of the world (*6*). Five holes were drilled during November and December of 1972 (*7*). The results for four of these are relevant to the question of the age of the sea floor (*8*). In addition, on leg 22 of the project holes were drilled in and near the Wharton Basin, and these help to define age gradients in the oceanic crust (*9*). Figure 1 shows the location of these holes and Table 1 gives the ages found or extrapolated for the sediments immediately above the basaltic basement.

Using the set of basal ages given in Table 1, one may draw a general set of isochron lines through the eastern Indian Ocean, as shown in Fig. 1.